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Time Variation of Optimum Azimuth for H-F Around-the-World Propagation

by

R. B. Fenwick and O. G. Villard, Jr.

March 1962

Technical Report No. 1004-2

Prepared under
Office of Naval Research Contract Nonr 225(24), NR 373 360
Jointly supported by the U.S. Army Signal Corps,
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(Office of Naval Research)

RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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Radioscience Laboratory
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Stanford University Stanford, California

ABSTRACT

If magnetic and auroral effects are neglected and the absorption of a radio wave in the lower ionosphere is assumed to be only a function of the sun's zenith angle, the attenuation due to absorption of a high-frequency signal propagated in a great circle around the world is a minimum when the signal path misses the subsolar point by the greatest possible margin. It follows that to a first order of approximation, and considering absorption loss only, the optimum azimuth of round-the-world (RTW) propagation from a specified point on the earth's surface would be expected to vary uniformly with time of day, always being normal to the direction from the transmitter to the subsolar point.

Measurements made at Stanford, California between August 1961 and January 1962 have confirmed that the optimum RTW azimuth is a function of time, and that this azimuth is closely approximated by the normal to the azimuth of the subsolar point vs time. Differences between the experimental and predicted curves are found to exist. In one example, it was possible to show that this was primarily due to lower F2-layer critical frequencies in the predicted azimuths, thus resulting in signal loss in the predicted directions due to penetration of the ionosphere. If this circumstance is taken into account, the average optimum azimuth of RTW propagation appears to be readily predictable for any point on the earth with good accuracy.

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TABLES

ILLUSTRATIONS

I. INTRODUCTION AND THEORY

It has long been known that the "optimum" direction for propagating round-the-world (RTW) high-frequency signals (i.e., the transmission azimuth resulting in greatest signal strength) varies with time of day and season [Ref. 1]. However, the precise explanation for this, and the detailed manner in which this azimuth varies with time, seems not to have been explored in detail. Measurements at Stanford, California, reported earlier [Ref. 2], showed that the normal diurnal variation was approximately the same as the variation of the azimuth of the "sun's wave fronts" at the point of observation. Later observation has corroborated this conclusion, and the way of specifying the azimuth has been made less awkward.

If the absorption due to the lower layers of the ionosphere is assumed to vary in a simple manner proportional to $(\cos \chi)^n$, where χ is the sun's zenith angle and n is determined from data [Ref. 3], and if magnetic-field effects are neglected, the attenuation due to absorption of a high-frequency signal propagated around the world is a minimum when the signal path "misses" the subsolar point by the greatest distance.

Let us say, for illustration, that the sun stands above the equator as shown in Fig. 1. There exists only one path which virtually avoids absorption, and that is the path on the twilight line which, in this instance, passes through the poles.

Consider transmitting from a point P somewhere on the sunlit hemisphere as shown in Fig. 1. Minimum absorption occurs when the RTW path transverses as little of the densely absorbing region as possible. This is satisfied when the ray path is at right angles to the direction from the transmitter to the subsolar point, as shown. Figure 1 shows qualitatively that this conclusion is reasonable. Paths through points P and Q with azimuths other than those shown will enter circular regions of higher absorption (nearer the subsolar point) and will accordingly suffer greater attenuation.

A proof of this assertion is as follows, referring to the coordinate system and designations in Figs. 2 and 3.

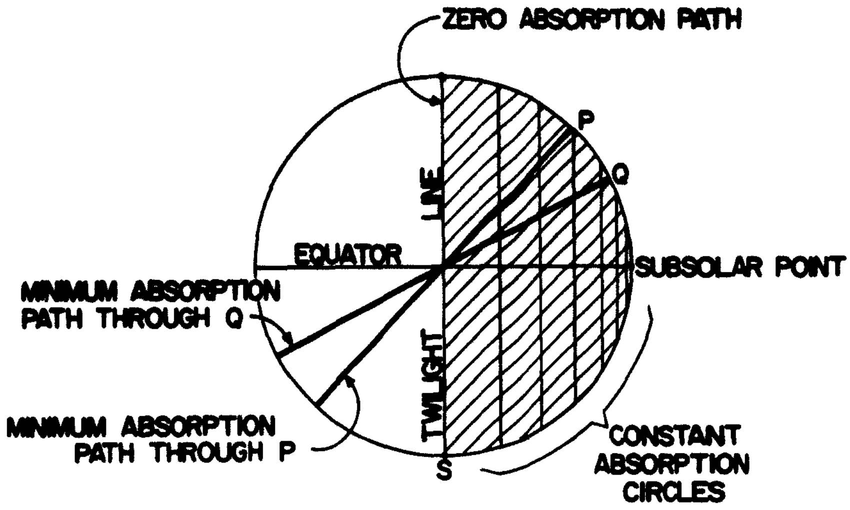

FIG. 1. EXAMPLES OF MINIMUM-ABSORPTION GREAT-CIRCLE PATHS ASSUMING THAT ABSORPTION IS A FUNCTION ONLY OF SUN'S ZENITH ANGLE.

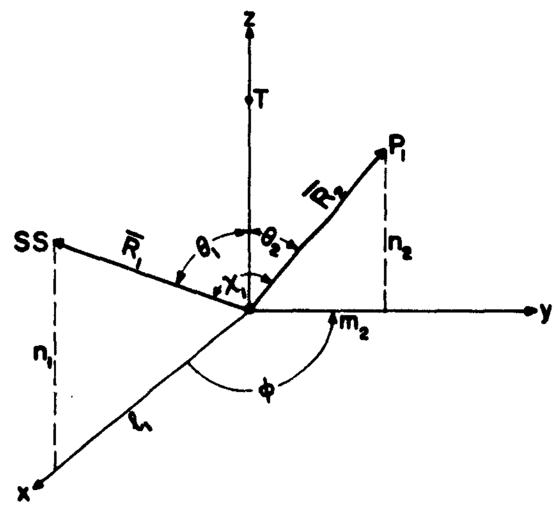

FIG. 2. GEOMETRY USED IN DETERMINATION OF THE MINIMUM-ABSORPTION GREAT-CIRCLE PATH THROUGH POINT T.

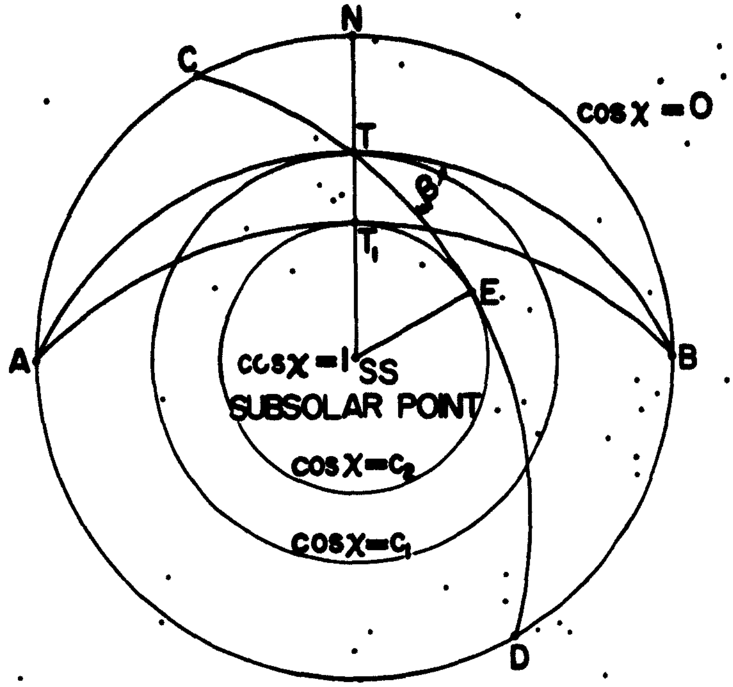

FIG. 3. THEORETICAL CIRCULAR APPROXIMATIONS TO GLOBAL CONSTANT-ABSORPTION CURVES, DETERMINING MINIMUM-ABSORPTION GREAT-CIRCLE PATHS THROUGH T (ATB), T_1 (AT_1B), AND E (CED).

Let the subsolar point be at point SS, coordinates $(R, \theta, 0)$. Let point $P(R, \theta_2, \pi/2)$ be a point on the earth's surface, and in the yz plane, for which the sun's zenith angle χ_1 is desired. R is the earth's radius. Let point T be the transmission point and, for simplicity, let $R = 1$. Then:

$$\overline{R}_1 \cdot \overline{R}_2 = l_1 l_2 + m_1 m_2 + n_1 n_2 = \cos\chi = n_1 n_2 = \cos\theta_1 \cos\theta_2 \tag{1}$$

Hence, for any point P_1 on the great circle through T which is normal to the great circle through T and SS,

$$\cos\chi = \cos\theta_1 \cos\theta_2 \tag{2}$$

Now, consider Fig. 3. The great circle through T for which the sun's zenith angle is described by Eq. (2) is ATB. If absorption along a path is given by:

$$\alpha = \alpha_o \int_{path} \cos \chi \, ds \qquad \cos \chi \geq 0$$

then

$$\alpha_{ATB} = 2\alpha_o \int_0^{\pi/2} \cos \theta_1 \cos \theta_2 \, d\,\theta_2$$

$$\therefore \alpha_{ATB} = 2\alpha_o \cos \theta_1 \tag{3}$$

Equation (3) shows that the total absorption of <u>any</u> path normal to line SS-N at T in Fig. 3 is proportional to $\cos \theta_1$, where θ_1 is the angle subtended at the center of the earth by SS and T. Hence, the absorption of path AT_1B is greater than the absorption of ATB.

Now consider a great-circle path CTD through T making some angle β with ATB. This path enters the circle $\cos \chi = c_1$ and is tangent to some other circle $\cos \chi = c_2$ at E. By symmetry, $\alpha_{CED} = \alpha_{AT_1B} > \alpha_{ATB}$, and the assertion is proved.

The azimuth normal to the direction of the subsolar point from a specified transmission point T is given by:

$$A = 90 - \cot^{-1} \left(\frac{\tan \delta \cos \phi}{\sin h} - \sin \phi \cot h\right) \tag{4}$$

where δ is the sun's declination

ϕ is the latitude of the point T

h is the sun's hour angle relative to the point T

This azimuth is plotted in Fig. 4 for $\delta = \pm 23^\circ 26'$ and $\delta = 0^\circ$, for Stanford, California ($\phi = + 37^\circ 25'$).

The curves of Fig. 4 would be expected to be an accurate estimate of the variation of optimum RTW-signal azimuth with local time provided that:

(1) D- and E-layer absorption is important in RTW propagation, and

(2) the azimuth of highest mean F2-layer critical frequency does not vary in a greatly different manner with time than does the minimum-absorption azimuth.

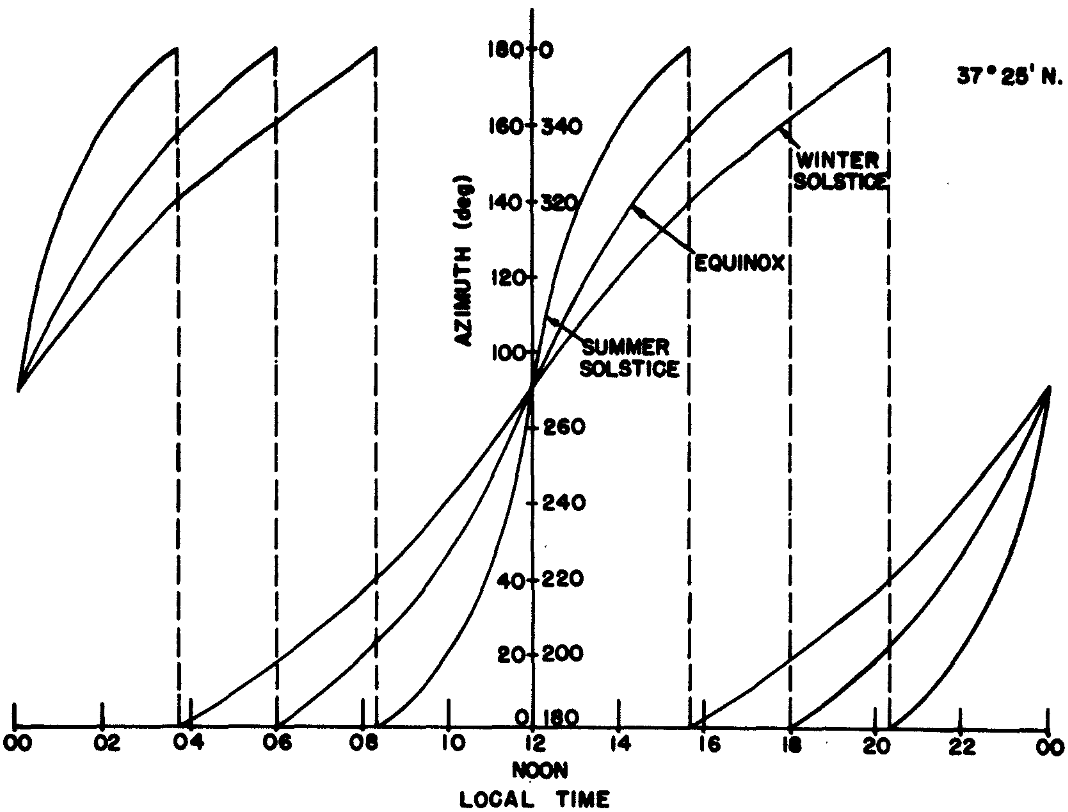

FIG. 4. PREDICTED VARIATION OF RTW-SIGNAL OPTIMUM AZIMUTH VS TIME FOR 37°25′ N, BASED ON MINIMUM ABSORPTION.

In an earlier report [Ref. 2], evidence was presented which indicated that RTW propagation in sunlit portions of the earth not near the poles was principally via ionosphere-ground-ionosphere hop modes. Hence, lower-ionospheric-layer absorption should be very important in determining the optimum azimuth of transmission. Further, it was shown from world maps of f_oF2 that the "twilight zone" azimuth should be preferred for RTW propagation since the minimum F2-layer critical frequencies on those paths were usually higher than the minimum F2-layer critical frequencies on other paths. (The twilight-zone azimuth for any point may be logically defined by Eq. (4)). However, it was also indicated that propagation in regions of minimum f_oF2 was via ionosphere-ionosphere tilt modes. For this reason, determination of optimum RTW azimuth from maps of f_oF2 becomes more difficult, since the degree of tilt of the F2 layer at any point in the world at a given time is not accurately known.

II. EXPERIMENTAL RESULTS

During the period 31 December 1961 to 8 January 1962 measurements of optimum RTW azimuth vs time of day were made at Stanford, California at 15.1 Mc. The period was quiet magnetically, and thus the results should be typical of normal conditions. In the experiment, 1-msec, 50-kw pulses were transmitted from a rotatable log-periodic antenna having a 3-db beamwidth of 64 deg. Receiving was performed by the same antenna. Hence, to the extent that the RTW propagation took place along great circles, the received RTW pulses were attenuated by the front-to-back ratio of the antenna (approximately 20 db).

Some of the records obtained on 31 December 1961 are shown in Fig. 5. The usual A-scope displays show log-detector output (35-pulse film integrations) vs time delay. Receiver bandwidth was 3 kc. Several interesting and characteristic features are apparent on these records. These include:

1. Optimum RTW azimuth varied from 270 deg to about 330 deg in the 5 hours shown.
2. The amplitude of the RTW signal increased as the time approached local sunset. (This is shown by the change of signal-to-noise ratio.)
3. The disappearance of the RTW signal was very rapid after sunset (compare 1736 PST records with 1810 PST records).
4. Disappearance of the RTW signal was accompanied by an increase in range and a decrease in amplitude of ground-backscatter in the optimum direction.
5. Since one major vertical division on the records represents about 10 db, the record of 1626 PST suggests that the azimuthal interval in which RTW propagation was possible had a width of approximately 26 deg, since the 6-db down points were nearly 90 deg apart, and the 6-db antenna beamwidth was 64 deg (assuming 64-deg, 3-db beamwidth transmitting, and 64-deg, 3-db beamwidth receiving from the back of the antenna).

The results of 6 days of such measurements (Fig. 5) are shown in Fig. 6. The broken line with a slope of 12 deg/hr appears to be a good estimate of the experimental data. The solid line is a theoretical curve obtained from Eq. (4). The theoretical curve is an excellent estimate of the experimental results during the morning hours, but becomes a poorer estimate in the afternoon (though still very good for many purposes).

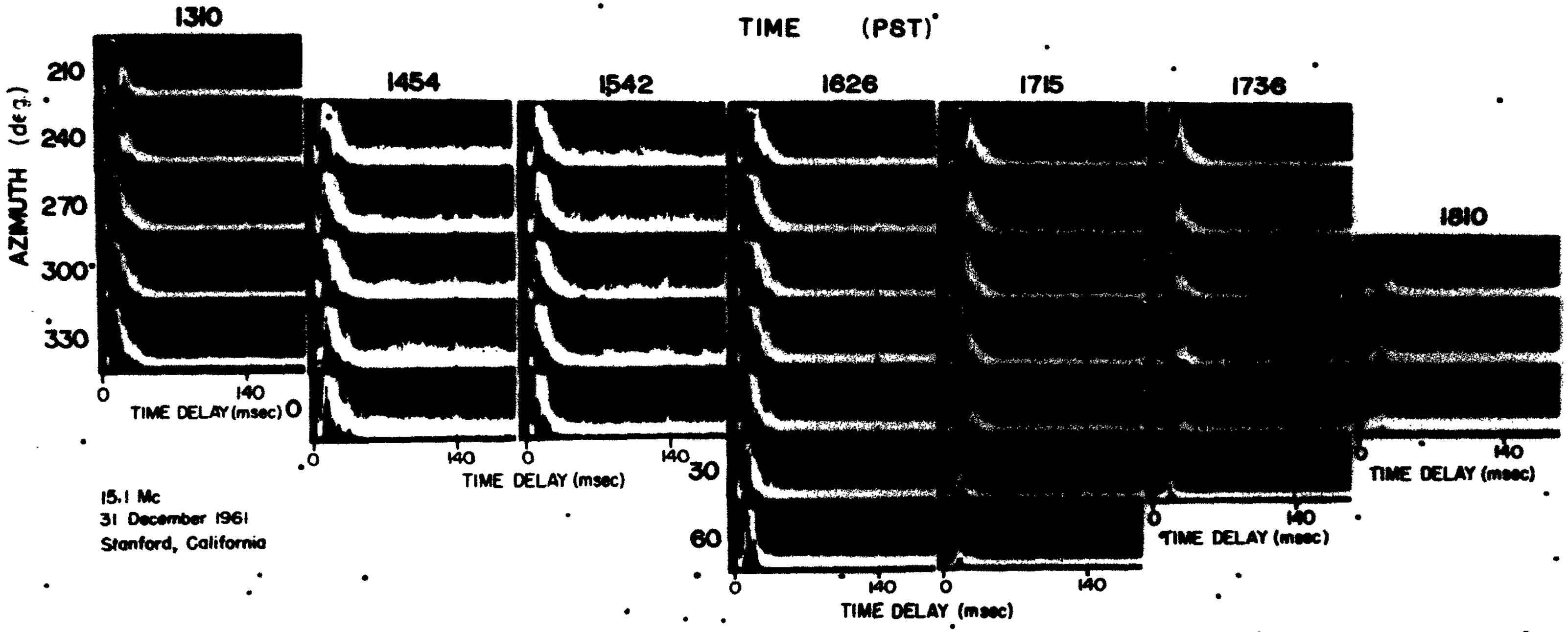

FIG. 5. EXAMPLES OF A-SCOPE DISPLAYS SHOWING VARIATION OF RTW-SIGNAL PROPAGATION CHARACTERISTICS WITH TIME.

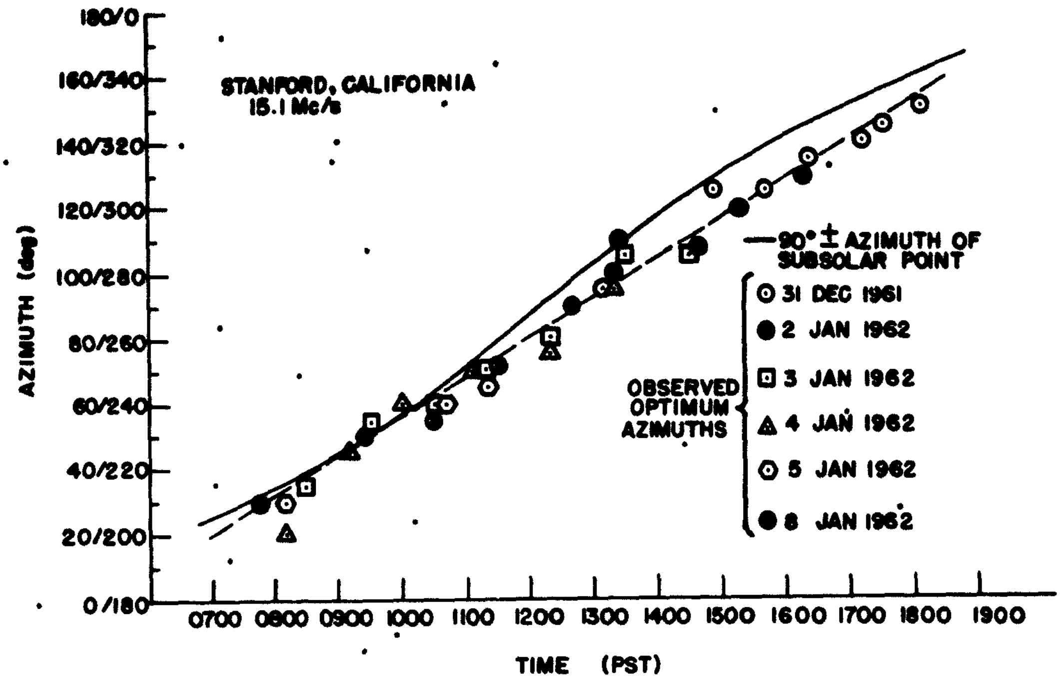

FIG. 6. EXPERIMENTAL POINTS AND PREDICTED CURVE FOR OPTIMUM RTW AZIMUTH VS TIME AT STANFORD, CALIFORNIA, JANUARY 1962, 15.1 Mc.

The National Bureau of Standards world maps of f_oF2 [Ref. 4] provide an insight into the difference between the experimental and theoretical curves. Figure 7 shows the map for 0800 PST in December, RASSN 50 (Running Average Sunspot Number). At this time, the two curves of Fig. 6 give optimum azimuths of approximately 33 deg (± 180 deg). Figure 7 shows great circles for 30-, 37-, and 51-deg (± 180 deg) azimuths, all passing through the point 37°25' N, 120° W. (Note that Stanford, California is actually at 123° W, but that the common point at 120° W is marked "Stanford," for simplicity.) The calibration marks on the curve appear at 1000-km intervals.

It has been shown [Ref. 2] that the variation of round-the-world MUF in the several hours following sunrise correlates closely with the variation of f_oF2 at the "control points," that is, the points 2000 km on either side of the observation point in the optimum azimuth. The control-point critical frequencies are listed in Table 1.

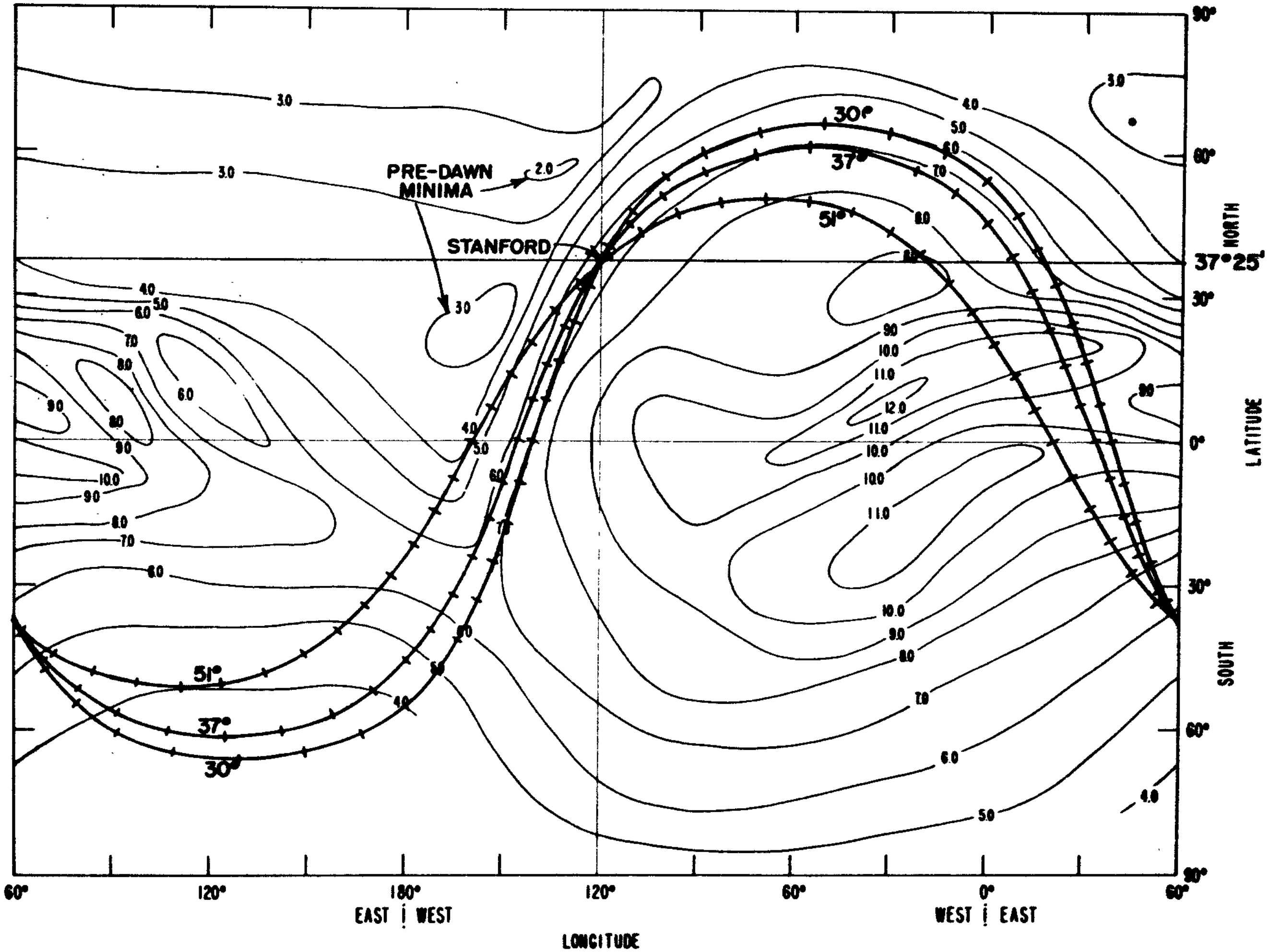

FIG. 7. PREDICTED WORLD-WIDE f_oF2 FOR 0800 PST, DECEMBER, RASSN 50, WITH THREE GREAT-CIRCLE PATHS THROUGH STANFORD, CALIFORNIA.

Table 1. Predicted Control Point f_oF2 for December, RASSN 50, for Varying Azimuth from Stanford, California, 0800 PST.

Azimuth (deg)	NE Control Point f_oF2 (Mc)	SW Control Point f_oF2 (Mc)	Minimum Control Point f_oF2 (Mc)
30	6.1	6.7	6.1
37	6.5	6.3	6.3
51	7.1	5.7	5.7

It is seen from Table 1 that the highest minimum-control-point f_oF2 occurs for a transmission azimuth between 30 and 37 deg. This is the azimuth observed experimentally and predicted theoretically on the basis of minimum absorption.

The theoretical and experimentally observed values of optimum RTW azimuth at 1600 PST, from Fig. 6, are 321 deg and 307 deg, respectively. The world map of Fig. 8 shows predictions of world-wide f_oF2 for 1600 PST (December, RASSN 50) and shows the great circles for 309-deg and 323-deg azimuths. Analogous to Table 1, Table 2 shows f_oF2 at the control points on the paths.

Table 2. Predicted Control Point f_oF2 for December, RASSN 50, for Varying Azimuth, 1600 PST.

Azimuth (deg)	NW Control Point f_oF2 (Mc)	SE Control Point f_oF2 (Mc)	Minimum Control Point f_oF2 (Mc)
309	8.1	7.3	7.3
323	7.7	8.0	7.7

If the criteria used at 0800 PST are applied here, it appears that the 323-deg path has the higher MUF. However, note that if the "first hop" is constrained to be ground-ionosphere-ground, as appears to be the situation for such paths in daylight [Ref. 2], the f_oF2 at other encounters with the ionosphere will determine the maximum RTW frequency and, consequently, the azimuth width which can propagate. In this instance, it

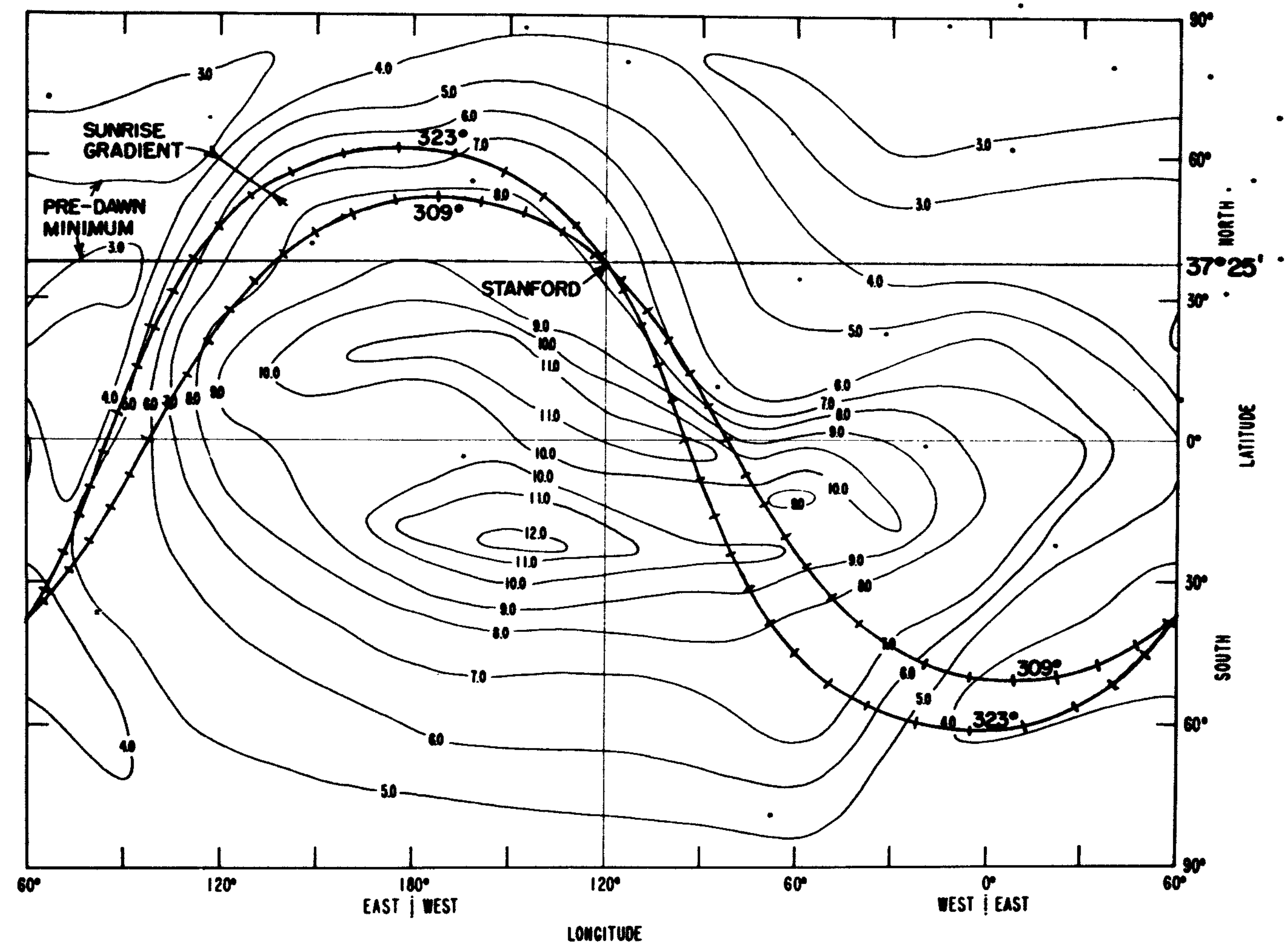

FIG. 8. PREDICTED WORLD-WIDE f_o F2 FOR 1600 PST, DECEMBER, RASSN 50, WITH TWO GREAT-CIRCLE PATHS THROUGH STANFORD, CALIFORNIA.

is interesting to compare the F2 critical frequencies 6000 km from Stanford. Table 3 shows the situation at these points.

Table 3. Predicted f_oF2 at points 6000 km from Stanford, California, December at RASSN 50, for Varying Azimuth, 1600 PST.

Azimuth (deg)	f_oF2 6000 km NW of Stanford (Mc)	f_oF2 6000 km SE of Stanford (Mc)	Minimum f_oF2 6000 km from Stanford (Mc)
309	8.2	10.0	8.2
323	6.5	10.0	6.5

Note that the minimum f_oF2 6000 km from Stanford is much higher for the 309-deg azimuth (approximately the experimentally observed value) than for the 323-deg azimuth (predicted on the basis of absorption). Further, note that the 323-deg path lies much nearer to the pre-dawn region of minimum f_oF2 and that the 309-deg path encounters much greater gradients of f_oF2. The 309-deg path f_oF2 decreases from 8 to 6 Mc in 2500 km in the region of maximum gradient while the 323-deg path gradients are primarily transverse, with the maximum longitudinal gradient being about 2 Mc in 6000 km.

Since the magnitude of the longitudinal f_oF2 gradient is a first-order indication of the ionospheric tilt present which can enable "tilt modes" to be launched, higher frequencies can be propagated through the region of greatest longitudinal f_oF2 gradient, for a given regional f_oF2. Also, in such regions, modes may propagate with a greater range of vertical angles of incidence on the layer without the layer being penetrated. If the great-circle path having minimum absorption will not support propagation at a given frequency due to MUF failure, but some other path has sufficient F2-layer critical frequencies (or greater longitudinal-layer tilts), clearly the "optimum" transmission azimuth for a given frequency cannot correspond to the minimum-absorption path.

Hence, it is concluded that the path lying closer to the East-West great circle in Fig. 8 is preferred from a critical-frequency standpoint,

and that the added energy that can propagate due to the presence of parallel ray paths (and possibly paths corresponding to different vertical takeoff angles) more than compensates for the increased absorption as the ray paths approach 270 deg.

Note that it is further suggested from Fig. 8 that the optimum azimuth will be a function of frequency, becoming slightly nearer to 270 deg as frequency is increased (up to the point of MUF failure at the 2000-km point SE of Stanford). It has not been attempted experimentally to verify this hypothesis, but such an effect has been qualitatively observed earlier [Ref. 2].

III. CONCLUSION

It has been predicted theoretically and verified experimentally that the optimum azimuth of RTW propagation is a function of time of day, and it has been shown experimentally at Stanford University for the winter solstice, 1961-62, that this azimuth agrees quite closely with the azimuth normal to the direction from Stanford to the subsolar point. It is concluded that it ought to be possible to predict the average optimum azimuth of RTW propagation quite closely, possibly to better than 10 deg, for any point on the earth at any frequency by use of the equation:

$$A = 90 - \cot^{-1} \left(\frac{\tan \delta \cos \phi}{\sin h} - \sin \phi \cot h\right)$$

and making a correction dependent on frequency derived from consideration of world maps of f_oF2.

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